Arctic Mixed Layer Dynamics

James H. Morison
Polar Science Center, Applied Physics Laboratory
University of Washington
Seattle, WA 98105-6698
Phone: (206) 543-1394; fax: (206) 616-3142; email: morison@apl.washington.edu

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LONG-TERM GOAL

Our long-term goal is to understand the dynamic and thermodynamic processes causing changes in the upper Arctic Ocean. In light of recent changes in the upper ocean structure, our long-term goals are shifting partly toward a better understanding of large-scale changes and their connection to global scale forcing.

OBJECTIVES

Our long-term goals have taken on new significance considering recent changes in the Arctic Ocean. The results of several expeditions in the 1990's indicate the upper Arctic Ocean is increasingly dominated by the Atlantic Water. The salinity of the upper 200 m of the Makarov Basin has increased by over 2.5 o/oo. A warm core of Atlantic Water now lies over the Lomonosov Ridge and the halocline is thinning. Our immediate objectives are to determine the effect of shelf processes and their changes on the upper ocean properties, and we hope to determine if similar changes in ocean properties have occurred before. Having seen the scope of the change in the last decade and recognizing that many observational programs have been curtailed, we aim to develop a community wide program of long-term observations and modeling to understand the changes in the Arctic. On a smaller scale, and using our newly developed Autonomous Underwater Vehicle (AUV) tools, we aim to understand the effect of horizontal variability in stably stratified, under-ice boundary layers.

APPROACH

This grant is taking several approaches to understanding the changing Arctic environment. First we are examining the role of shelf processes and their effect on the upper ocean. To do this we are comparing U.S. and Russian data to results from a basin wide ice-ocean model. Second, this grant augments our efforts to develop the Study of Environmental Arctic Change (SEARCH). This consists of organizing workshops, giving talks on SEARCH, and preparing the SEARCH Science Plan and related material. Finally, this grant funds the PI to supervise a graduate student, Mr. Dan Hayes, in analyzing data gathered with an Autonomous Underwater Vehicle (AUV) during the Surface Heat Balance of the Arctic Ocean (SHEBA) study.

WORK COMPLETED

Under this grant, the PI and Jinlun Zhang have begun to examine the character of shelf processes with Zhang's coupled ice-ocean model. We are choosing parameters for which we have long term data. One of the best examples is sea level pressure, for which there are records going back more than 50 years.

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Under our previous ONR grant Vladimir Pavlov (then of the Russian Arctic and Antarctic Research Institute) analyzed sea level and other long Russian records. These results are being used to validate the model and ultimately relate changes on the Russian shelves to overall changes in the Arctic.

SEARCH development has progressed well beyond anything we had envisioned. This grant has supported part of the PI's efforts to develop SEARCH. We also receive funding from the NSF Office of Polar Programs Arctic Section and early in 2000 we received a new NSF grant for an expanded SEARCH Project Office. The focus of SEARCH is to understand Onami, the complex of interrelated pan-arctic changes we have begun to see in recent decades. Several developments have enhanced the strategy and scope of SEARCH. Perhaps the most significant of these has been the establishment of an Interagency Working Group for SEARCH (IWGS) to come up with an interagency SEARCH plan. This gives SEARCH an organizational focus in the funding community, in addition to the effort in the PI community-provided SEARCH Science Steering Committee or SSC. The IWGS formed informally in late 1999 and included representatives from NSF, NOAA, ONR, NASA, and DOE. We prepared a SEARCH presentation kit and spoke to the Interagency Arctic Research Policy Committee (IARPC) in February 2000. SEARCH was featured in the IARPC 5-year Plan for 2000, with text prepared by Chuck Meyers of NSF-OPP and myself. IARPC officially formed the IWGS and gave approval for the IWGS to develop interagency plans for 2001, 2002, and 2003. The 2001 Interagency Plan was completed and we anticipate approval from IARPC in September 2000. The Plan for 2002 will be completed in late fall of 2000. The most important milestone will be completion of the 2003 plan in February 2001. This will include an Interagency Budget Request.

The PI community has also made good progress. The SEARCH SSC is chaired by the PI of this grant. Its main task is to prepare a SEARCH Science Plan. This has been delayed somewhat by the expansion of the scope and strategy of SEARCH, but we were recently able to make public the Draft SEARCH Science Plan. It is now freely available at the SEARCH Web site: http://psc.apl.washington.edu/search/index.html. It must be completed along with the IWG 2003 Interagency Budget Request in February 2001. In an effort related to development of the science plan, the PI completed an invited article (Morison, 2001) for the *McGraw-Hill 2001 Yearbook of Science & Technology* describing the Arctic Oscillation and its impact on the Arctic.

The third major development is that, SEARCH has become part of U.S. CLIVAR. The aim of CLIVAR is to understand climate variability. U.S. CLIVAR has been composed of three elements, Pacific, Atlantic, and Pan-American, with a panel for each. We sought and received acceptance of SEARCH as an arctic component of U.S. CLIVAR. A SEARCH-CLIVAR working group is being established to coordinate the SEARCH physical climate activities with the CLIVAR panels.

The SHEBA AUV work under this grant consists of advising graduate student Dan Hayes in development of a Kalman smoothing technique for determining turbulent fluxes from AUV motion and applying the technique to Autonomous Micro-conductivity and Temperature Vehicle (AMTV) data gathered at SHEBA to understand the summertime under-ice boundary layer. Hayes is supported under ONR Naval Ocean Modeling Program grant N00014-96-5033. We have made excellent progress on the Kalman smoothing work. We have submitted a paper (Hayes and Morison, 2000) on the subject to *the Journal of Atmospheric and Oceanic Instrumentation*. Hayes passed his General Exam in late May. The committee approved his thesis proposal to use the SHEBA AMTV results in conjunction with modeling to understand the effect of horizontal variability in stably stratified boundary layers.

In related work, the PI co-authored two chapters in the *Encyclopedia of Ocean Sciences* to be published by Academic Press. McPhee and Morison (2001) describe basic planetary boundary layer physics in the context of the under-ice boundary layer, and Morison and McPhee (2001) describe the unique elements of ocean-ice interaction that control the exchange of heat, salt, and momentum between the ocean and sea ice.

RESULTS

The results of Pavlov et al. (1999) produced under our previous grant showed a positive trend in Russian Arctic sea level observations over the last 50 years. Our modeling effort is meant in part to explain this in the context of the Arctic change so that we can use historical records of sea level as long-term proxy of change. Figure 1 is an example of initial results. It compares the relatively anticyclonic (clockwise) ocean conditions (Proshutinsky and Johnson, 1997), with raised central Arctic Ocean sea surface, characteristic of pre-1990s climatology and the less domed, relatively more cyclonic (counterclockwise) conditions of the 1990s. The left panel represents the annual average sea surface elevation for 1961 simulated using the multi-level, coupled ice-ocean, model of Zhang et al. (1998) (by contrast, the Proshutinsky and Johnson [1997] model is barotropic). Our model was driven with NCEP reanalysis atmospheric fields. The right panel shows the result for 1993. One of our key hypotheses about the changes in the Arctic environment is that they are related to the rise in the Arctic Oscillation (AO) index (Thompson and Wallace, 1998). Associated with the rising AO is a drop in surface atmospheric pressure over the Arctic Ocean and a cyclonic spin up of the polar vortex. This cyclonic atmospheric circulation is thought to drive a more cyclonic ocean circulation with decreased sea surface elevation in the center of the basin and increased sea level at the ocean margins. The AO was relatively low in 1961 and high in 1993. The model does indeed show that relative to 1961, the sea surface was on average lower in the central basin and higher along the Russian coast in 1993. The implications for the fate of Russian river water and the formation of the cold halocline is important. Increased coastal sea level will tend to move river water eastward toward the Beaufort Sea instead of allowing it to mix across the shelves to produce cold halocline water. Thus, the pattern shown in Figure 1 would contribute to the observed decrease in Beaufort Sea salinity (McPhee et al. 1998) and the reduced cold halocline thickness (Steele and Boyd, 1998) of the 1990s.

With regard to the SHEBA AUV work, the Hayes and Morison (2000) paper shows excellent agreement between turbulent vertical velocity spectra from the AMTV Kalman smoother and from fixed sensors. The spectra agree well within the confidence limits to a wavelength of 2 meters, nearly the theoretical limit of the 1.6 m hull length. We were able to improve accuracy and extend the frequency response well beyond what we had achieved earlier by accounting for the pitching moment caused by the variation in vertical water velocity along the length of the hull.

We have found some unexpected results in the SHEBA data that should have wide applicability. We see that by virtue of boundary layer shear, when the ice moves over a region that has been warmed and freshened, it drags dense water over less dense water. This reduces the stability locally and promotes mixing even though the average buoyancy flux is stabilizing. A similar effect would apply anywhere there is shear and horizontal patchiness in density.

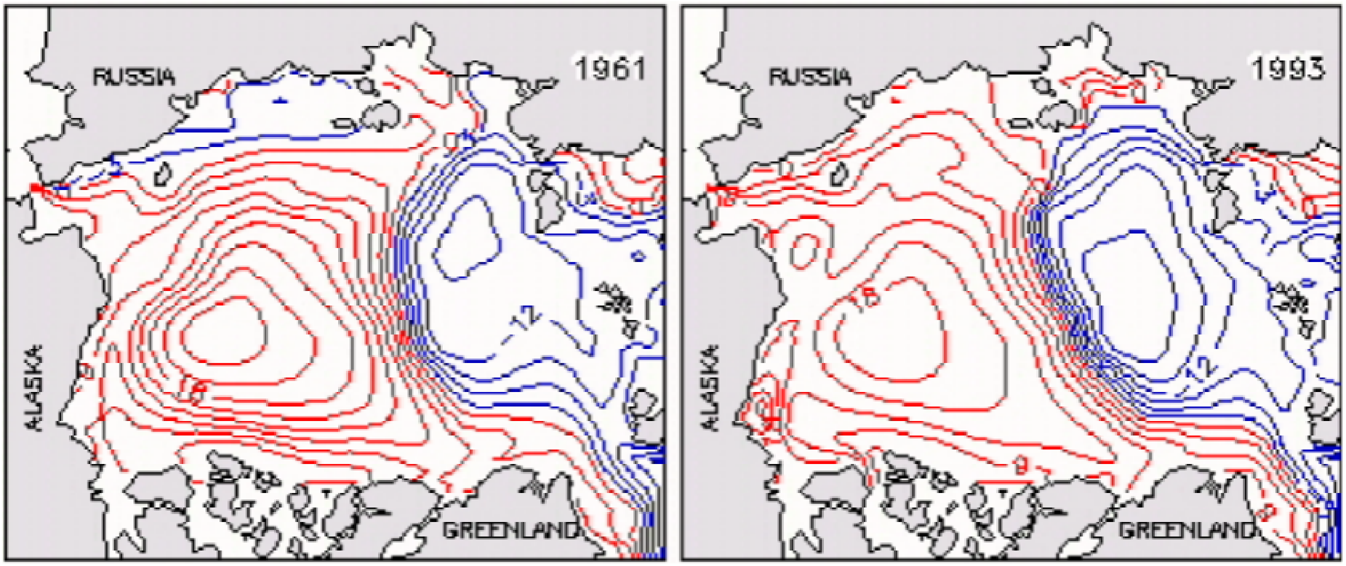

Figure 1. Yearly average sea surface elevation from the coupled ice-ocean model of Zhang et al. (1998) for 1961 (left) and 1993 (right).

IMPACT/APPLICATION

It is of utmost importance that the changes in the Arctic Ocean be studied in detail. They may represent a decadal-scale change or the start of a longer-term shift. In either case examining the evolution of the changes over time will likely tell us much about the interplay of the Arctic with the rest of the globe. The Study of Arctic Change has relevance to the Navy because it involves significant changes in the upper ocean and coastal areas. These are areas important for naval operations, and it is here that oceanographic conditions are most likely to be different in the future than when examined heavily in the 1980s by the Navy. The Arctic change may be even more important for its effect on the northern sea route. Other nations, notably Japan and Russia are examining the potential of the northern sea route for trade. If the Arctic change affects navigability of the northern sea route, this may change shipping patterns between Asia and northern Europe, and the strategic significance of the Arctic Ocean.
The impact of the AUV oriented research will be to provide a technique whereby nearly any AUV can provide turbulence data as a side benefit to other sampling it carries out. This is because the proposed technique requires only data from a vehicle's on-board motion sensors. Used with simple vehicles, the technique will yield spatial maps of turbulent energy. Used with sophisticated AUVs, the technique will also yield spatial maps of vertical fluxes of the other variables being measured. Such maps will be the key to identifying dynamically critical areas of the Autonomous Ocean Sampling Networks (AOSN) sampling regions and will be crucial to determining the budgets of heat, salt, biomass and pollutants. This information is critical to our SHEBA research because the under-ice boundary conditions are strongly nonhomogeneous. The SHEBA results are broadly applicable because they show that horizontal variability may alter the effect of buoyancy flux on the average stratification of boundary layers.

TRANSITIONS

See Impact/Applications above for transitions related to the Arctic change work. The Kalman smoothing method and vehicles like the AMTV could find direct military transitions. We visualize such AUVs making clandestine surveys of littoral areas. The method of extracting information on water

motion from vehicle motion would have application in determining the wave energy in areas of planned amphibious assault. The technique may also find application as a non-acoustic detection and tracking tool. This would find application in "smart" and acoustically quiet weapons that could detect the wakes of vessels and follow them. Torpedoes using the technique in real time could conceivably follow turbulent ship wakes to their targets.

RELATED PROJECTS

Dan Hayes is supported for the Kalman smoother work by ONR Naval Ocean Modeling Program grant N00014-98-1-5033. The SHEBA project is funded jointly by the National Science Foundation and the ONR High Latitude Program. The Arctic change elements of this work are related to the Study of Environmental Arctic Change Project Office effort funded by NSF.

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